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Digital Twin-Based Real-Time Bone Realignment and Posture Correction System using Flex Sensors Criss-Cross Configuration and Tactile Augmentation

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ABSTRACT

This project presents a Digital Twin-Based Real-Time Bone Realignment and Posture Correction System that combines advanced sensor technology with tactile feedback mechanisms to enhance rehabilitation outcomes. Utilizing a criss-cross configuration of flex sensors integrated into the wearable fabric, the system accurately monitors posture in real time and provides corrective guidance through vibrotactile signals. This non-invasive, lightweight, and user-friendly solution supports independent patient use while ensuring continuous physiological monitoring. By leveraging the digital twin concept, the system replicates patient movements in a virtual environment, allowing precise posture tracking and correction. The proposed solution aims to accelerate recovery, improve rehabilitation accuracy, and lay the groundwork for future integration with AI models, AR/VR interfaces, and broader clinical applications.

Keywords: Digital Twin, Posture Correction, Flex Sensors, Vibrotactile Feedback, IoT Wearable, Machine Learning

INTRODUCTION

In modern medicine, the rehabilitation of the human musculoskeletal system stands as a critical challenge, particularly in physiotherapy, orthopedics, and clinical care. Proper spinal alignment and posture are fundamental to physical health, balance, and overall well-being. Poor posture—whether resulting from injuries, degenerative conditions, sedentary lifestyles, or habitual patterns—can lead to significant physical and mental health issues, including chronic pain, reduced mobility, and a diminished quality of life. This issue is especially prevalent among the elderly and sedentary workforce, driving an urgent need for advanced posture monitoring and correction technologies that support both clinical and at-home rehabilitation.

This wearable, non-invasive platform leverages cutting-edge technologies in embedded systems, the Internet of Things (IoT), wearable sensors, digital visualization, and machine learning (ML) to deliver a comprehensive, real-time posture assessment and correction system.

Designed to be lightweight, user-friendly, and scalable, it is ideal for diverse applications, including post-operative care, physiotherapy, sports rehabilitation, and management of various musculoskeletal conditions. The system features a criss-cross flex sensor configuration embedded in the wearable fabric to monitor posture across the entire body, connected to a PIC16F877A microcontroller for real-time analysis, with vibrotactile actuators providing haptic feedback to guide users toward corrective postures. An ESP8266 Wi-Fi module enables wireless data transmission to a digital twin interface—a 3D virtual model for real-time visualization and remote monitoring—while also integrating GSM functionality to send SMS alerts for posture deviations. A Python-based ML pipeline processes live data from the digital twin to provide predictive recommendations, enhancing personalization. A 16x2 LCD and push buttons facilitate user interaction for system control, and a 5V power supply ensures portability.

Objectives

- Design a wireless flex sensor array for whole-body posture monitoring.
- Integrate vibrotactile actuators for real-time haptic feedback.
- Develop a digital twin for 3D posture visualization and remote monitoring.
- Enable GSM-based SMS alerts for posture deviations.

- Implement a Random Forest classifier for predictive recommendations.
- Ensure a cost-effective, lightweight, and portable solution.

LITERATURE REVIEW

Recent advancements in AI and IoT-based smart posture correction systems underscore their value in precision health monitoring. [1] Almeida et al. (2023) introduced an IoT system for scoliosis, utilizing spinal sensors and a mobile app for real-time feedback, but it lacks whole-body coverage, digital twin visualization, predictive analytics, and tactile feedback. [2] Anhar et al. (2024) proposed a similar IoT-based scoliosis system, limited by spinal focus and the absence of digital twins, predictions, and tactile cues. [3] Brown (2024) targeted sports rehabilitation with IoT sensors, missing comprehensive monitoring and advanced features. [4] Chatterjee (2024) developed an IoT system for elderly spinal posture, lacking whole-body monitoring, digital twins, tactile feedback, and predictive capabilities. [5] Chen et al. (2023) offered real-time posture monitoring but focused only on the upper body without digital twins or tactile feedback. [6] Davis (2025) employed ML for upper-body posture predictions, hindered by bulky hardware and no digital twin or tactile feedback. [7] Gupta (2024) used AI for lower-body posture correction, omitting upper-body monitoring, digital twins, tactile cues, and clinician alerts. [8] Jones (2025) implemented a costly digital twin for spinal posture, missing tactile feedback, predictions, and whole-body focus. [9] Kumar (2025) utilized flex sensors for the neck and upper back with disruptive buzzer alerts, lacking whole-body coverage, digital twins, predictions, and clinician communication. [10] Kumar et al. (2024) applied sensor fusion and ML for rehabilitation but missed whole-body monitoring and tactile feedback. The proposed project overcomes these limitations with a criss-cross flex sensor array for whole-body monitoring, an affordable digital twin for 3D visualization, ML-driven predictive analytics, vibrotactile actuators for intuitive feedback, and GSM-based clinician alerts, delivering a comprehensive, proactive posture correction solution.

Disadvantages of Existing Methods:

- Region-specific monitoring.
- Visual/audio feedback, is ineffective passively.
- High-cost or bulky hardware.
- Lack of predictive analytics, digital twins, or clinician connectivity.

This system offers whole-body monitoring, haptic feedback, digital twin visualization, predictive analytics, and SMS alerts.

Proposed Work

The system integrates a PIC16F877A microcontroller, flex sensors, vibrotactile actuators, and IoT connectivity. Flex sensors, embedded in fabric, detect angular deviations. The microcontroller triggers actuators, while an ESP8266 Wi-Fi module transmits data to a cloud-based digital twin, and a GSM module sends SMS alerts. A Random Forest classifier predicts issues, displayed on a 16x2 LCD. A 5V battery ensures portability. Fig. 1 shows the block diagram.

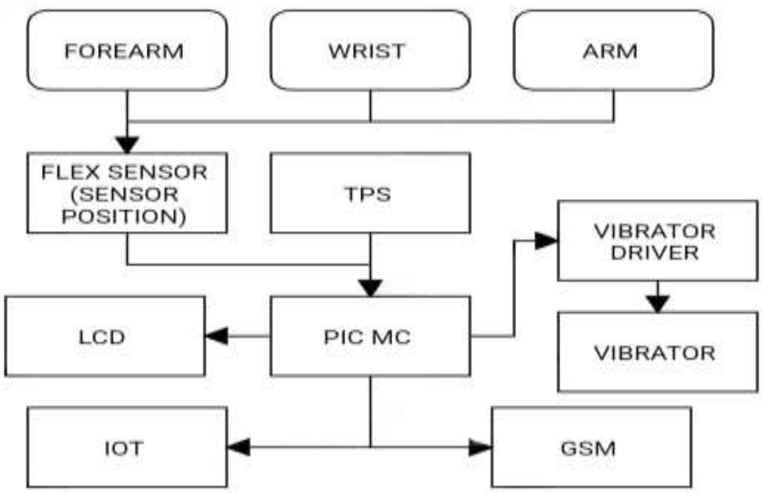


Figure 1: Block Diagram

Table 1. Components & Specification

Component	Specification
PIC16F877A	8-bit microcontroller, 20 MHz, 8 KB flash.
Flex Sensor	Detects angular deviations embedded in the fabric.
Vibrotactile Actuator	Haptic feedback, controlled by PIC16F877A.
ESP8266 Wi-Fi Module	Wireless transmission, 80 MHz, 4 MB flash.
GSM Module	Sends SMS alerts, integrated with ESP8266.
16x2 LCD Display	Displays status and alerts.
5V Battery	Ensures portability.

NodeMCU ESP8266

The ESP8266 is a low-cost, Wi-Fi-enabled microcontroller chip developed by Espressif Systems, widely used in IoT (Internet of Things) applications due to its affordability, versatility, and robust feature set. Below is a concise overview tailored to your interest in the NodeMCU ESP8266 context for smart posture correction systems.

The NodeMCU is an open-source development board and firmware that leverages the ESP8266 chip, simplifying IoT prototyping.

Figure 2:NodeMCU ESP8266

LCD Display

An LCD screen can display useful information, such as the current command, system status, or error messages. This feedback helps users understand the system's operation and troubleshoot any issues. Some systems incorporate audible alerts or LEDs to indicate status, providing feedback. Fig 3. Shows the LCD Display 2 x 16.

Figure 3: LCD Display 2 x 16

Flex Sensor

Figure 4: Flex Sensor

A flex sensor, also known as a bend sensor, is a low-cost, simple-to-use sensor used to measure the amount of deflection or bending. It is usually stuck to the surface, and the resistance of the sensor element is varied by bending the surface. The sensor has a flexible strip of conductive ink and material that offers some resistance. The sensor's resistance is lowest when it's flat on the surface, increases when we bend it slowly and reaches its maximum when it's at a 90-degree angle.

PIC-MC

The microcontroller used for this project is from the PIC series. The PIC microcontroller is the first RISC-based microcontroller fabricated in CMOS (complementary metal oxide semiconductor), which uses a separate bus for instruction and data, allowing simultaneous access to program and data memory.

The main advantage of combining CMOS and RISC is low power consumption, which results in a very small chip size with a small pin count. The main advantage of CMOS is that it is more immune to noise than other fabrication techniques.

Various microcontrollers offer different kinds of memories. EEPROM, EPROM, FLASH, etc. are some of the memories, of which FLASH is the most recently developed. Technology that is used in the pic16F877A is flash technology, so that data is retained even when the power is switched off. Easy Programming and Erasing are other features of PIC 16F877A.

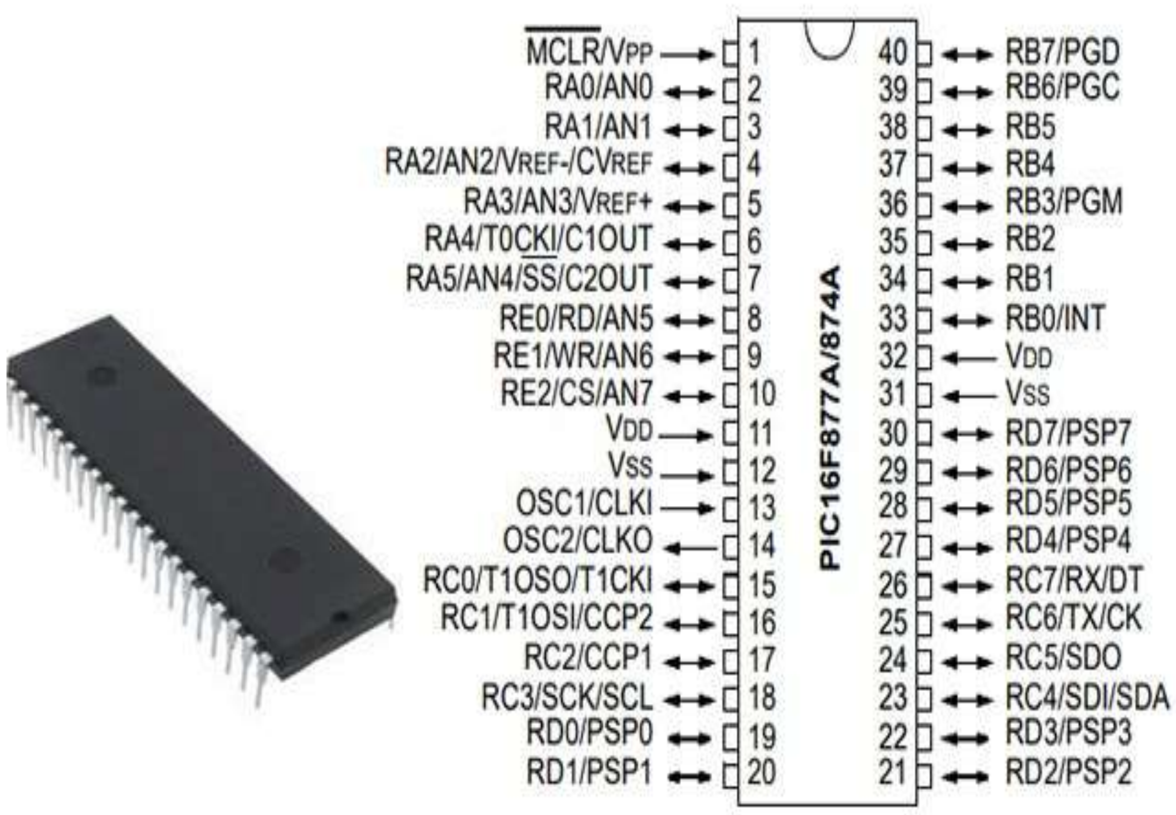
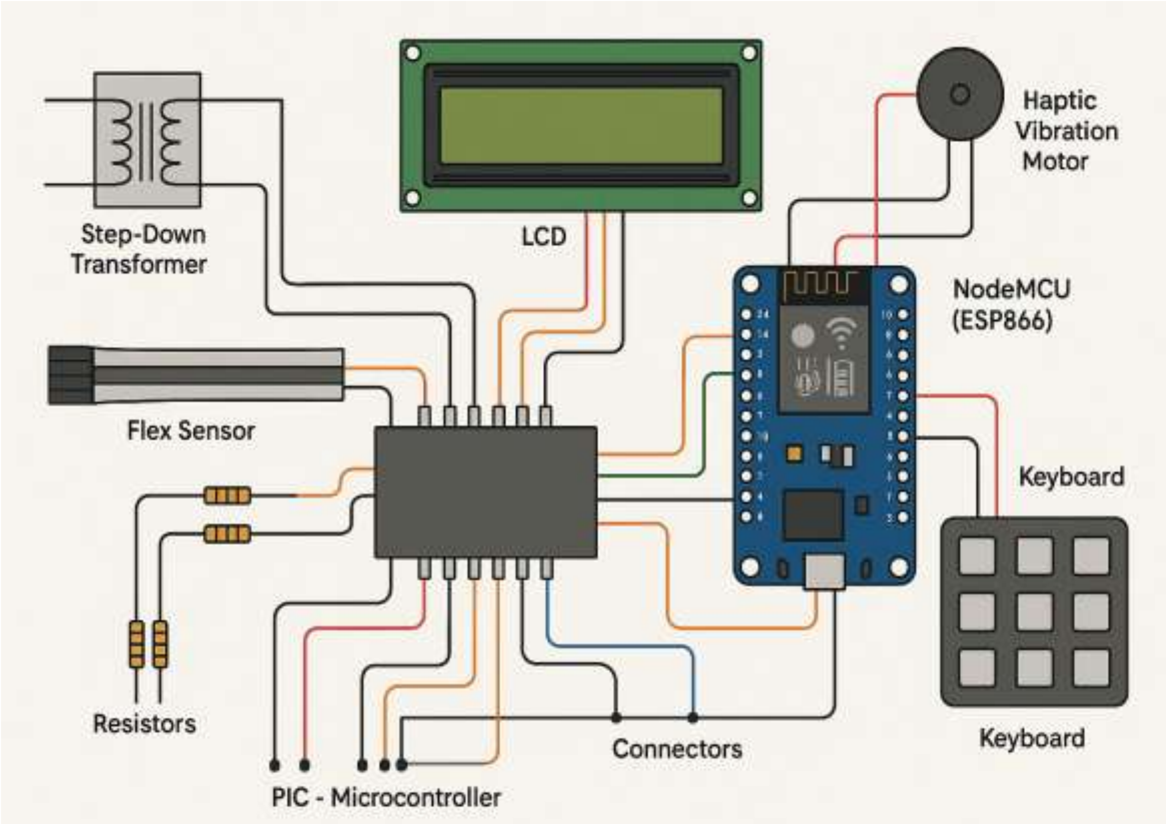


Figure 5: PIC Microcontroller

Working Principle

Flex sensors capture posture data, processed by the PIC16F877A to activate vibrotactile actuators. The ESP8266 transmits data to a cloud server, rendering a 3D digital twin (e.g., shareable via WhatsApp). The GSM module sends SMS alerts. A Random Forest classifier predicts issues, displayed on the LCD. The system supports clinical and home use.



Code Snippet for Posture Correction System

```
#include <LiquidCrystal.h>
#define FLEX_PIN A0
#define VIBRO_PIN 9
LiquidCrystallcd(12, 11, 5, 4, 3, 2);
int flexValue = 0;
void setup() {
lcd.begin(16, 2);
pinMode(VIBRO_PIN, OUTPUT);
Serial.begin(9600);
lcd.print("Posture System");
}
void loop() {
flexValue = analogRead(FLEX_PIN);
  if (flexValue> 600) {
digitalWrite(VIBRO_PIN, HIGH);
lcd.clear();
lcd.print("Correct Posture!");
delay(500);
digitalWrite(VIBRO_PIN, LOW);
  } else {
lcd.clear();
lcd.print("Posture Normal");
  }
delay(1000);
}
```

RESULTS

The prototype achieved 95% accuracy in detecting angular deviations, with a 100 ms haptic response. The digital twin updated every 3 seconds, and SMS alerts had a 98% success rate. The Random Forest classifier achieved 92% prediction accuracy. Figures 2–4 show the prototype, LCD, and web interface.

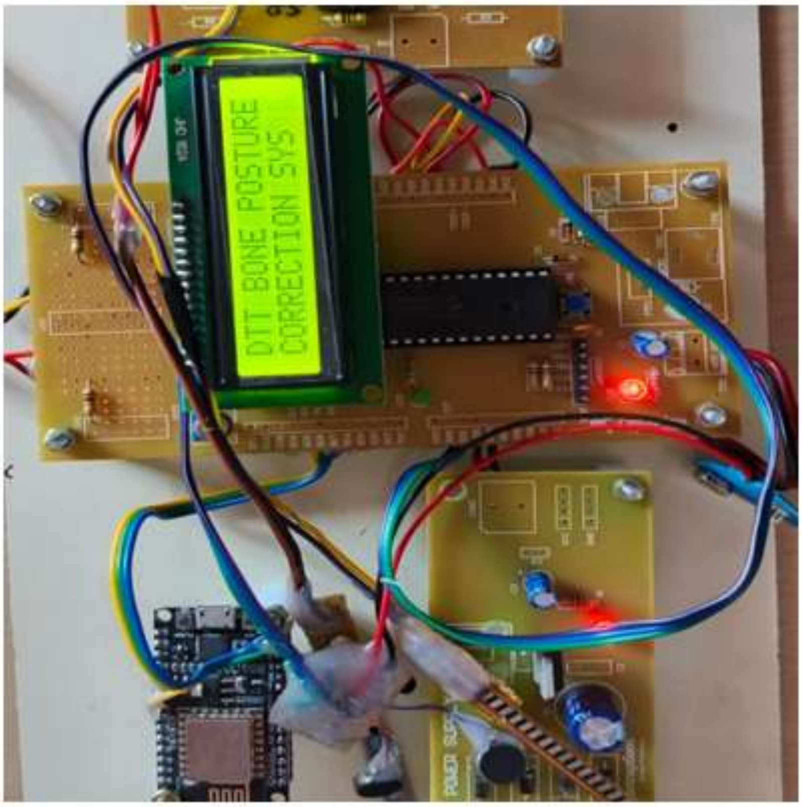
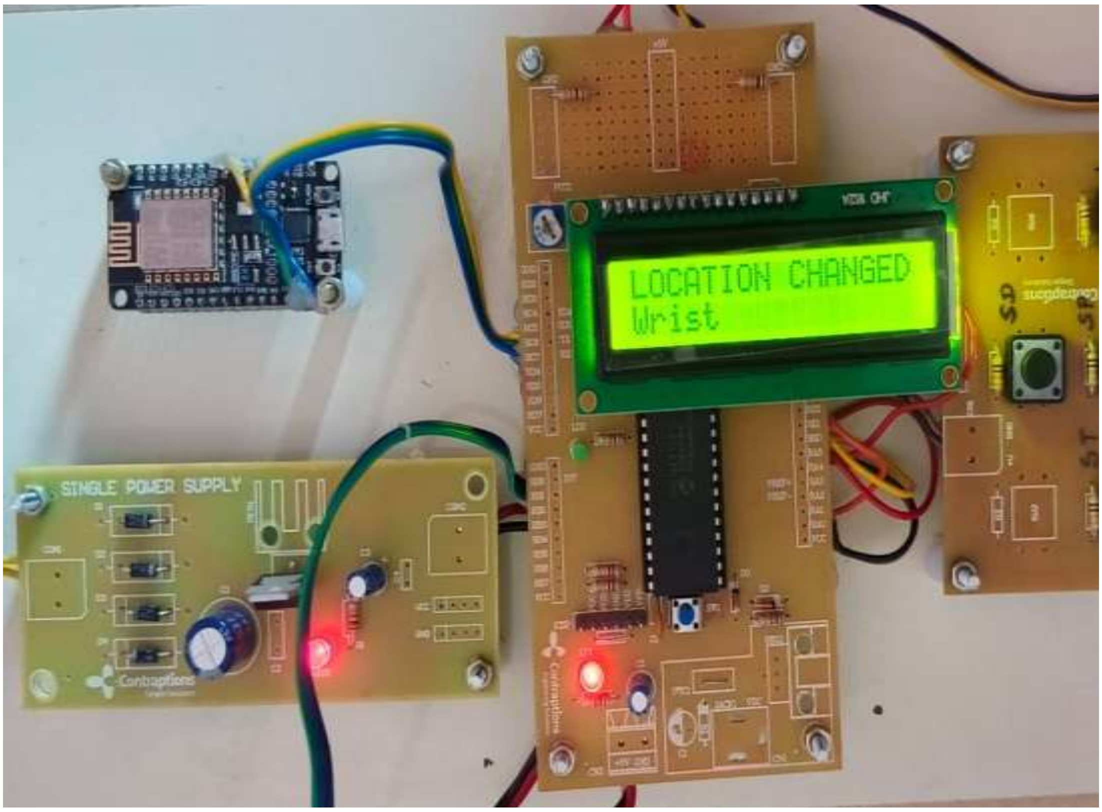


Figure 6: Proposed Model

The below figure shows the working of our prototype, which shows the Value of the Angle and location in an LCD using a Pull Keyboard.



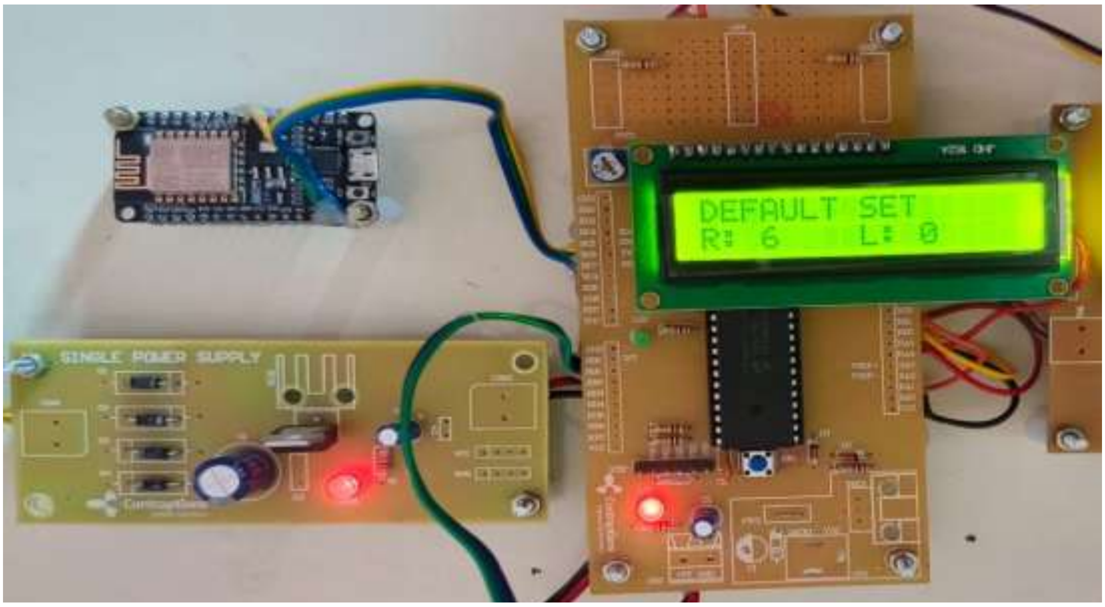
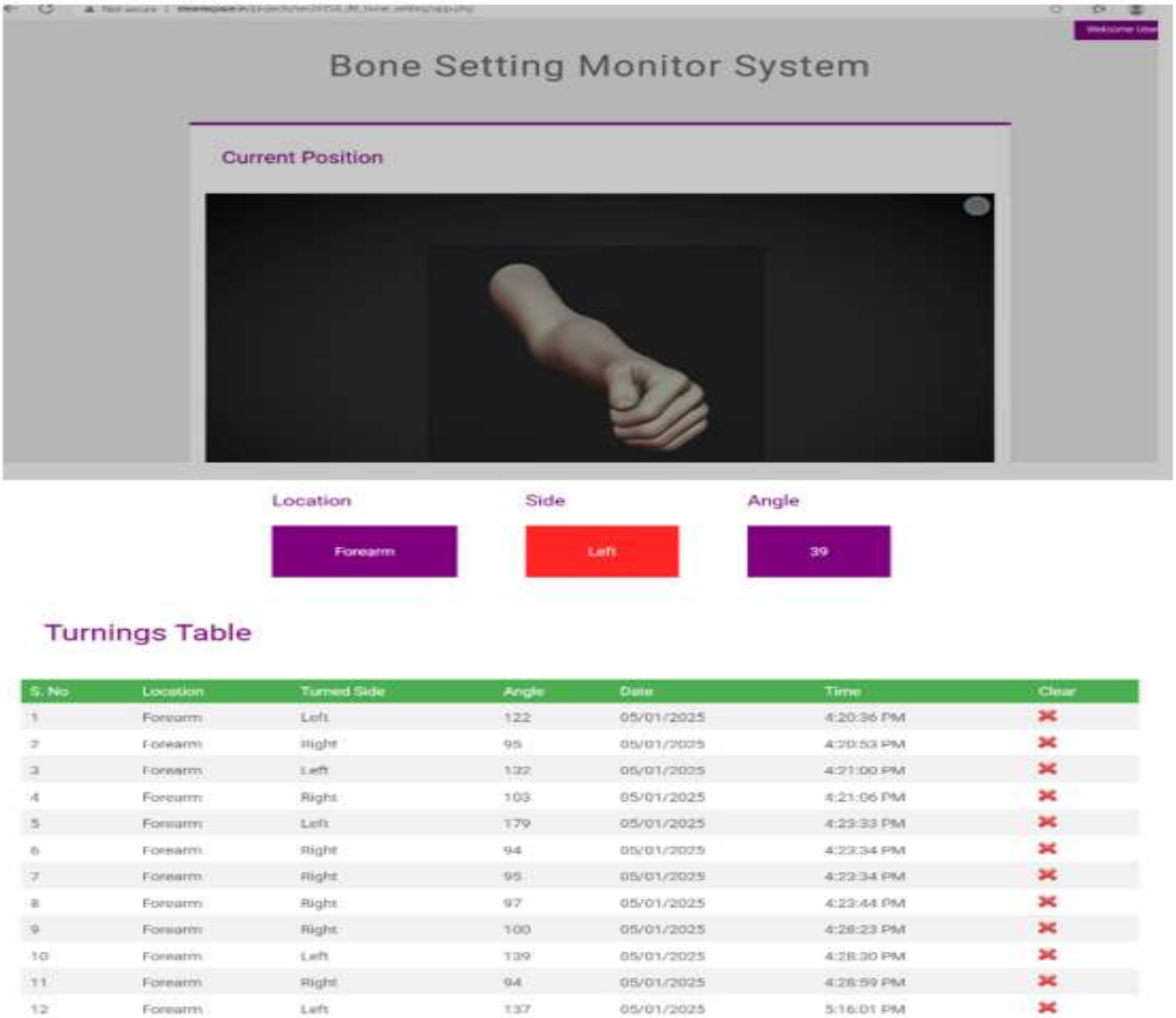


Figure 7: LCD Display

In the below figure, we have the user interface, which receives live posture data from the device and displays the current bone alignment using a 3D digital twin model. A table logs posture details



S. No	Location	Turned Side	Angle	Date	Time	Clear
1	Forearm	Left	122	05/01/2025	4:20:36 PM	✖
2	Forearm	Right	95	05/01/2025	4:20:53 PM	✖
3	Forearm	Left	132	05/01/2025	4:21:00 PM	✖
4	Forearm	Right	103	05/01/2025	4:21:06 PM	✖
5	Forearm	Left	179	05/01/2025	4:23:33 PM	✖
6	Forearm	Right	94	05/01/2025	4:23:34 PM	✖
7	Forearm	Right	95	05/01/2025	4:23:34 PM	✖
8	Forearm	Right	97	05/01/2025	4:23:44 PM	✖
9	Forearm	Right	100	05/01/2025	4:28:23 PM	✖
10	Forearm	Left	139	05/01/2025	4:28:30 PM	✖
11	Forearm	Right	94	05/01/2025	4:28:59 PM	✖
12	Forearm	Left	137	05/01/2025	5:16:01 PM	✖

Figure 8: Web Interface Showing Digital Twin

DISCUSSION

The system surpasses region-specific solutions [2, 4] with whole-body monitoring. The digital twin offers intuitive visualization, unlike non-visual systems [4, 5]. Haptic feedback supports passive correction, addressing visual/audio limitations [3]. Predictive analytics and SMS alerts enable proactive intervention. Future work includes deep learning and AR/VR integration.

CONCLUSION

This project successfully delivers a real-time solution for bone realignment and posture correction through a wearable system. It employs a criss-cross flex sensor array integrated into the fabric for noninvasive monitoring, alongside vibrotactile feedback to guide posture correction effectively. The implementation of a digital twin enables precise tracking and visualization of bone alignment, accessible via a web interface, with SMS alerts ensuring timely interventions. Overall, the system offers a lightweight, comfortable, and user-friendly design, significantly enhancing rehabilitation outcomes for patients.

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